Science Overview

Peter Stockman

&

John Mather

Origins,

Scientific Processes,

Science Drivers

The HST & Beyond Committee

- In 1994, the HST & Beyond Committee, chartered by AURA and NASA, considered the needs of the UV/Opt./IR community in the era after HST (& SIRTF).
- The Committee made 3 recommendations (Alan Dressler 1996)
  - Extend the operational lifetime of HST to > 2010 at a reduced cost.

    → **HST Cheap Ops**
  - Study the development of a large (> 4 m dia.) ***passively cooled*** space telescope optimized for 1-5µm.

    → **NGST**
  - Establish the technology for large baseline interferometric missions.

    → **SIM, TPF**

The Astronomical Search for Origins & Planetary Systems Theme

Next Generation Space Telescope

SRB

A Special Time for Humankind

- The HST & Beyond Committee recognized that major NASA missions should address scientific issues of broad importance to scientists and the Public.
- They identified two scientific questions that can be answered by recent advances in technology and science, questions that may be answered only once in a human history. Both answers are to be found in space, in the infrared!
  - Q1: How did our universe, our galaxy, and our solar system form?

Cosmological expansion moves spectra to the near infrared (1-5µm,NIR). Dust that hides star forming regions can be penetrated by NIR and mid-infrared (5-30µm,MIR) radiation.

  - Q2: Are there other worlds like ours?

The Earth shines brightest at ~10µm in the MIR.

NGST

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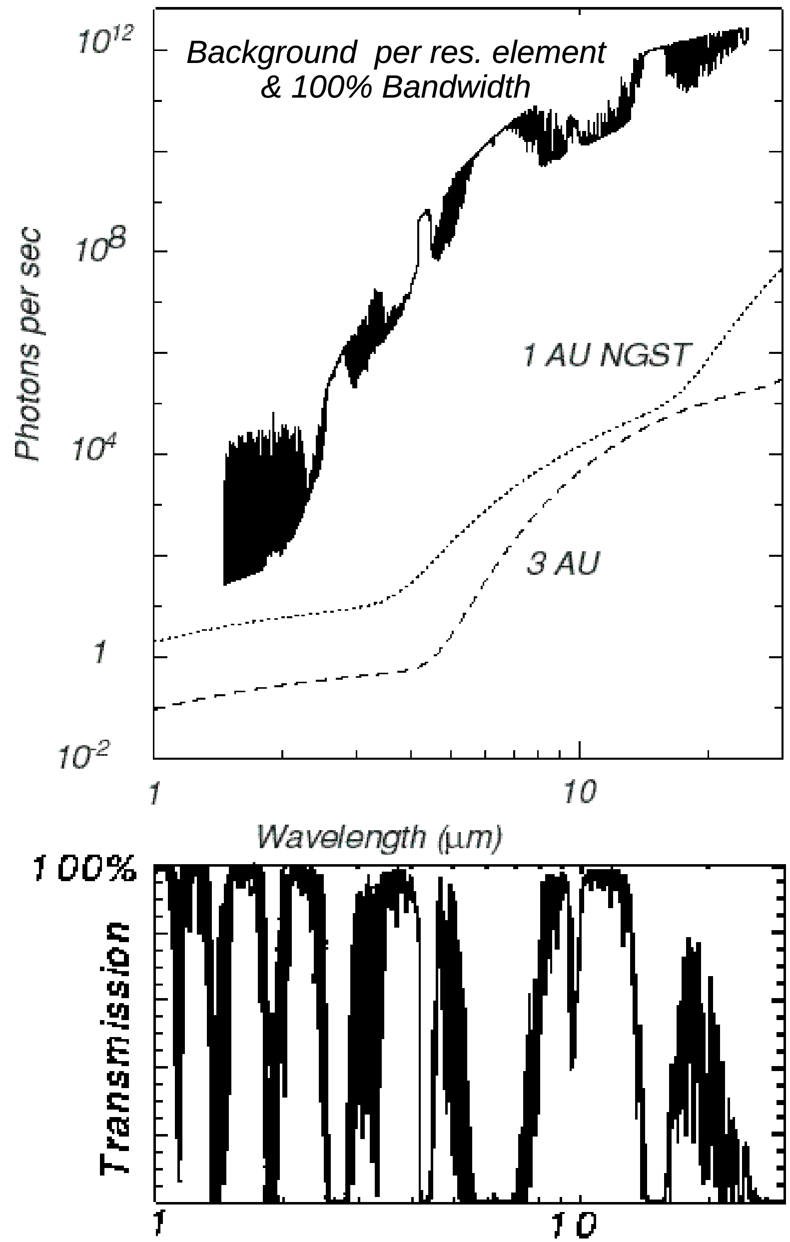
Why do we need an IR space telescope?

- Space affords diffraction-limited performance over large fields of view.
- Space permits the cooling of large optics to near cryogenic temperatures.
- The Earth's atmosphere is 10^2 to 10^8 brighter than the background from scattered and reprocessed Sunlight and starlight in our Galaxy.



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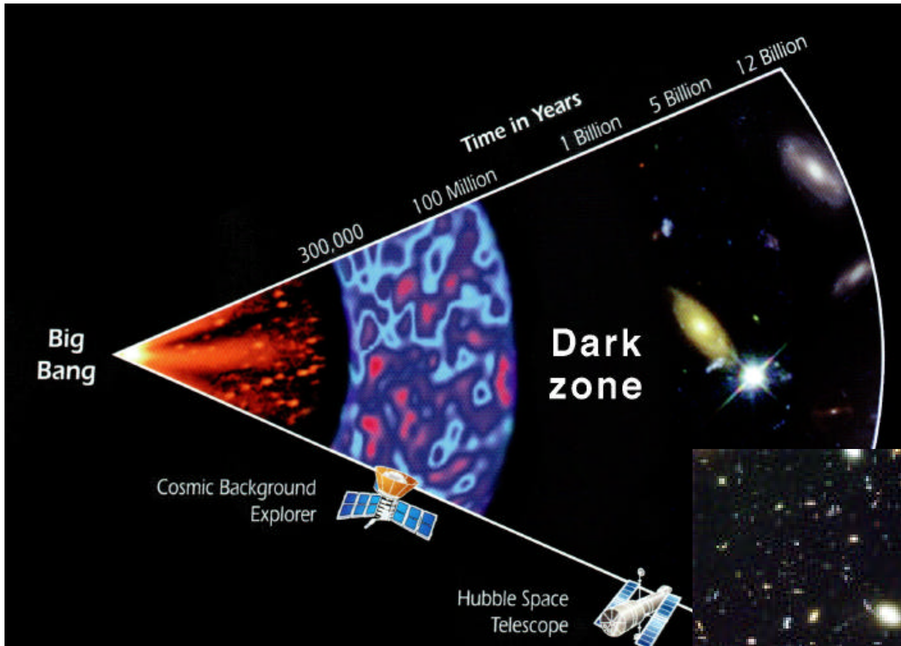
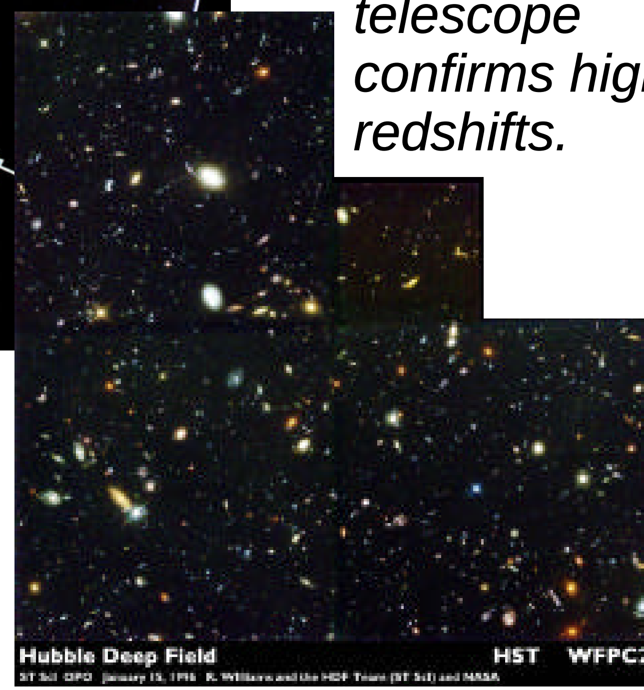
The *Hubble Deep Field (HDF)* points to the Origins of Stars and Galaxies and the Future of*NGST*





- *HDF is deepest image of the sky*
- *Keck telescope confirms high redshifts.*

- *Faint galaxies seen to ~ 12 billion light years - 1 -2 billion years since Big Bang.*
- *To view Dark Zone, NGST needs HST resolution - galaxies/ early structures are small!*

NGST Will See the Earliest Star and Galaxy Formation

~ 1 nJy sensitivity in NIR to detect early starbursts

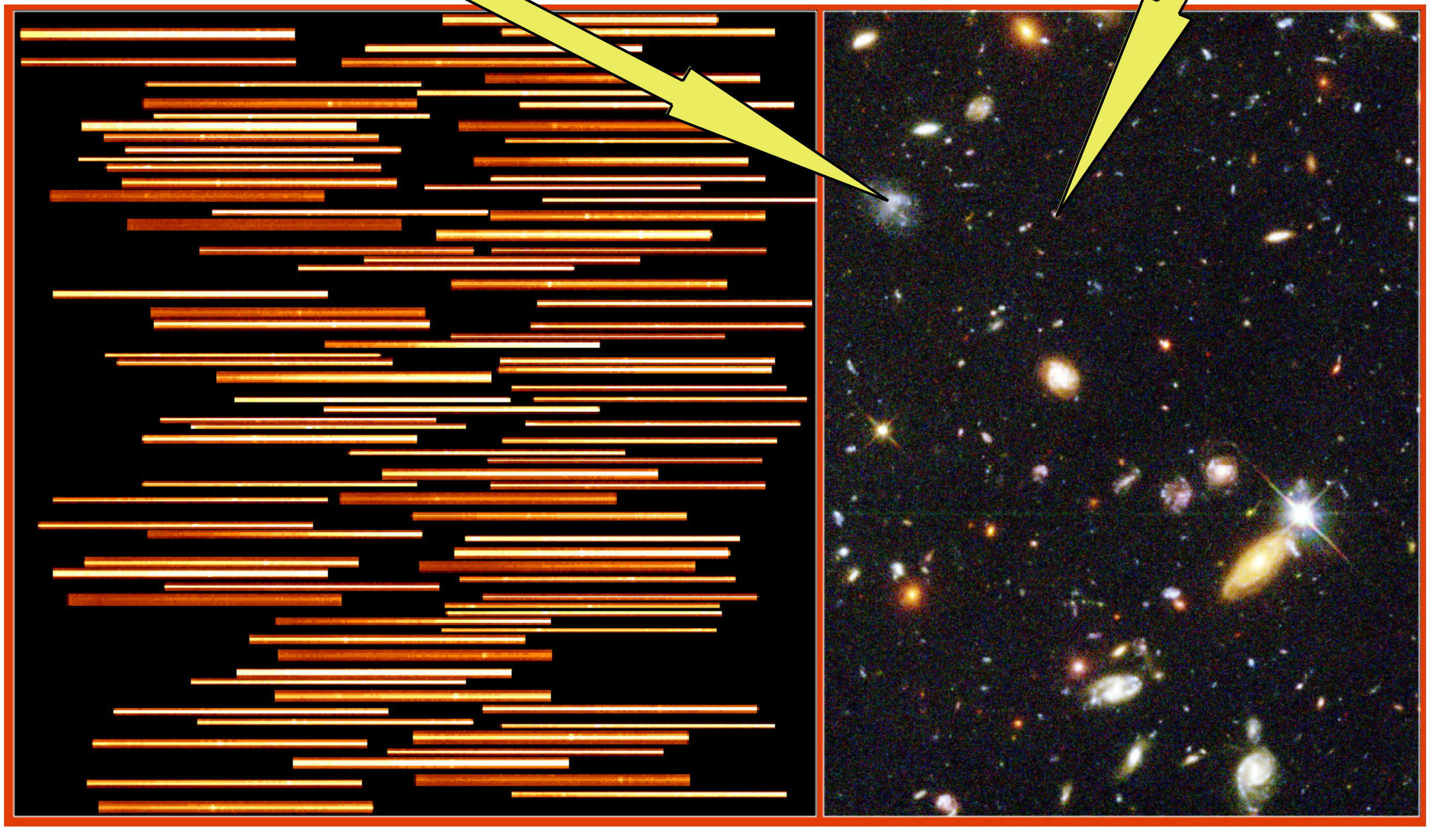
HST-like Resolution Eliminates Confusion

30 arcsec NGST field, 10,000 s in I,J,K

Early Objects May be Rare

> 10^4 "nearby" galaxies per 4'x4' field, 10^{2-4} protogalaxies

< 10 Supernovae per year!



Multi-object Spectroscopy Confirms Identity

Wide Field of View is Important

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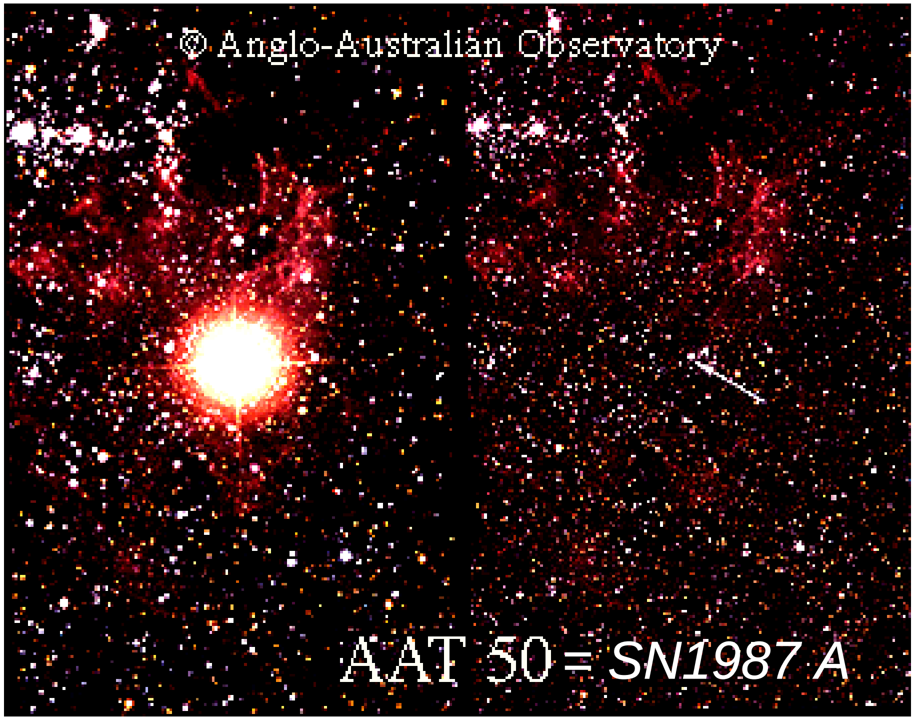
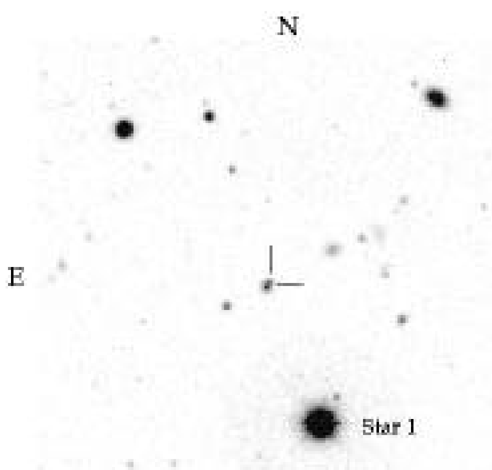
NGST Can See Supernovae from the Earliest Star Formation



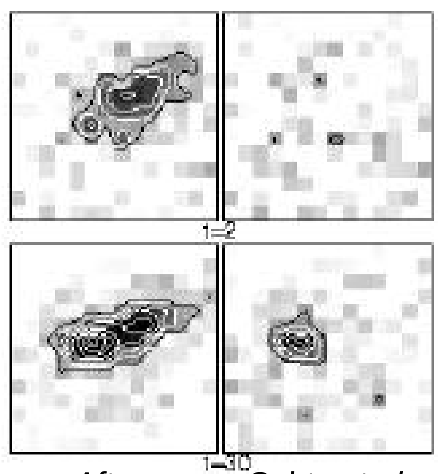
- Supernovae seed the Universe: The Origins of Life.
- Supernovae are the brightest objects in the Early Universe. Great probes of IGM!

NGST can see SNe to z ~ 10-15 !



SNe at z ~ 0.5

Before



After *Subtracted*

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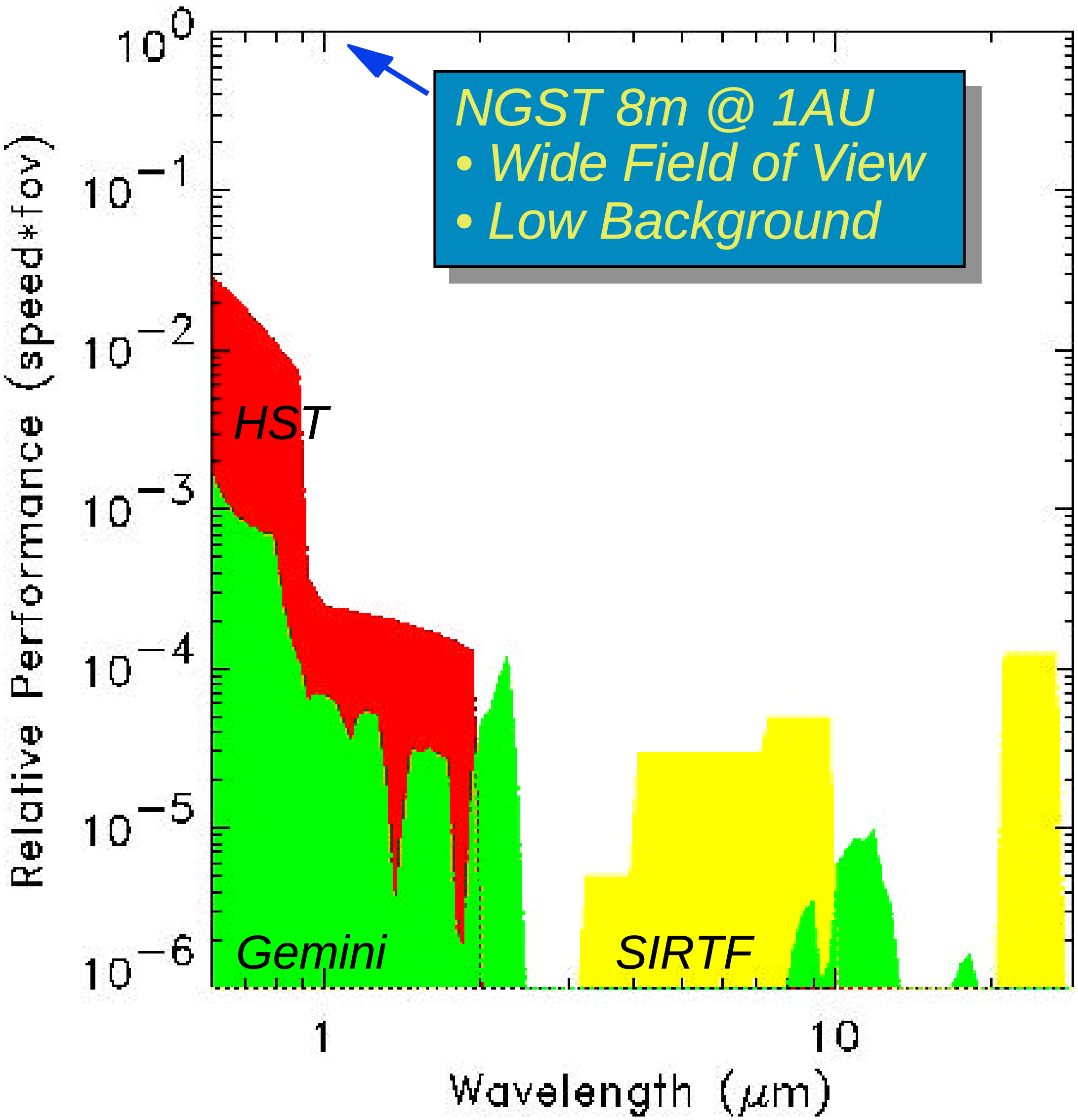
NGST Provides > 10^3 Speed Improvements from 0.5-30 µm Over Other Planned Facilities



• Visible Science
- Kuiper Belt Survey
- Planet Searches
- Stellar Pops in the Galaxy & Local Group of Galaxies

• MIR Science
- Protoplanets & protostellar obj.
- Dust covered galactic nuclei & star formation
- Interstellar Med. studies.
- Solar System atmospheres

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Developing A Science Strategy

- Guideline: HST & Beyond Committee & OSS Long Range Plan
  - Studying the Origins of Galaxies, Stars, & the Elements of Life.
  - General Observatory Facility (i.e. not PI mission)
- Volunteer Science Working Group develops Design Reference Mission: *NGST: Visiting a Time When Galaxies Were Young*

- Ad Hoc Science Working Group will refine DRM for Science PNAR
  - Solicits inputs from international astronomy community
  - Considers other Spacecraft/Operations needs per program.
  - Consolidates & Prioritizes for Project & NASA HQ

NGST

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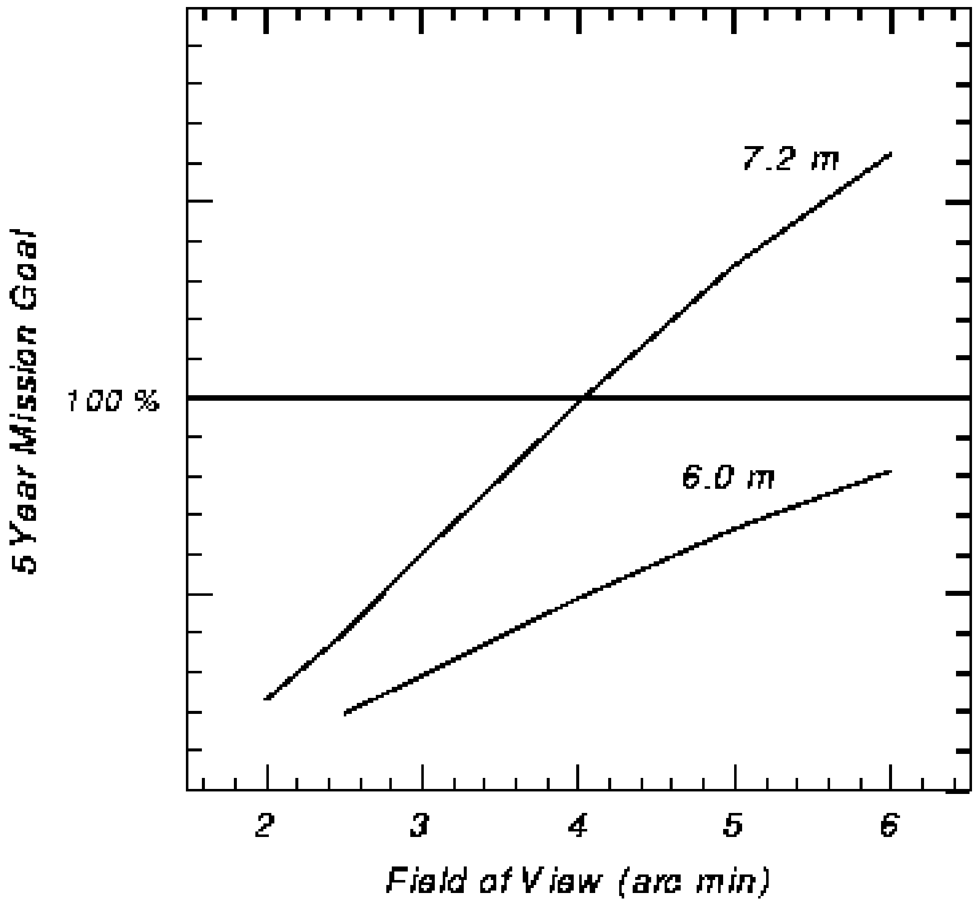
Design Reference Mission/ How NGST Will be Used

- **Motivations**
  - **Important Science Goals consistent with OSS Origins Long Range Plan**
  - **NGST Unique**
- **Input Programs and Targets**
  - **Science and Technical Details/Program Requirements**
  - **Output: Estimated Number of Hr/Days per Science Program**
  - **ASWG prioritization**
- **NGST Goal is to perform DRM in 2.5 years, perhaps as ~20-30 peer reviewed, key programs**

Insert DRM Table Here from Geithner

DRM Supports NGST Trade Studies & Metrics



Ancillary Rqmts identified

- **Real Time Operations**
- **Moving Target Capabilities**
- **Continuous Viewing Zones**
- **Quick Response**
- **etc.**

DRM can be run versus spacecraft and instrument configurations.

- **Mirror Diameter & Temp**
- **Instrument FOV and performance**
- **Visible & MIR options**

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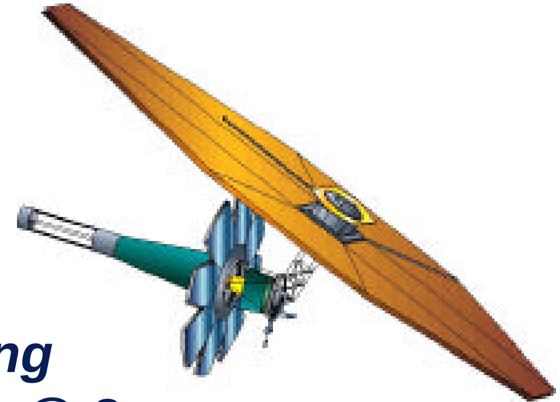
Science Drivers



- ***Excellent Sensitivity***
  ~1 nJy level for NIR imaging
- ***HST-like angular resolution @ 2 µm***
- ***Wide Field of View***
  > 10 square arcminutes.
- ***2-D imaging faint spectroscopy with low-medium spectral resolution (low det. noise)***

Visible	1-5 µm core	5~>30 µm MIR

Needs high quality optics on small scales.

Needs extra cooling for low noise Si:B or HgCdTe detectors

Next Generation Space Telescope

Space Telescopes

A Primer

Pierre Y. Bély

NGST Mission Architect

Space Telescope Science Institute

Next Generation Space Telescope

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Point Spread Function - Resolution

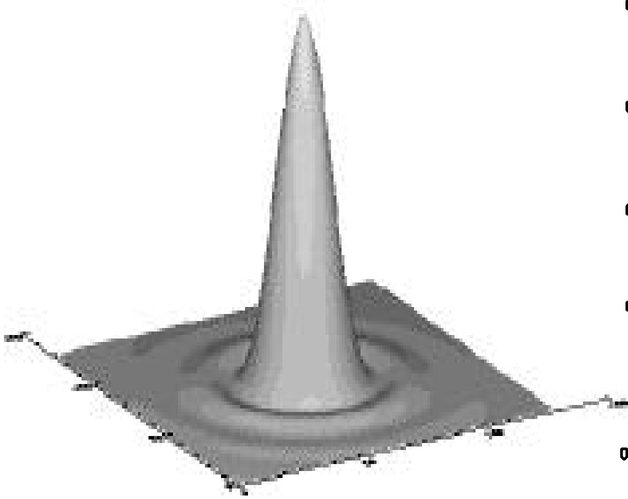
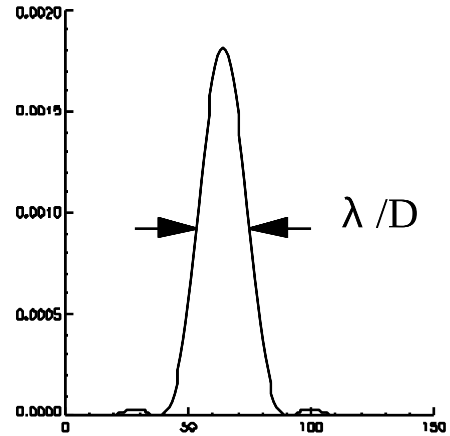
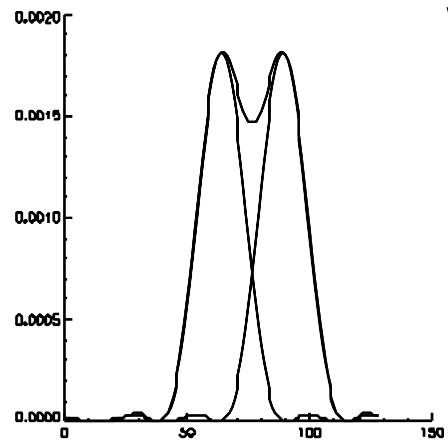


Image of point source given by a telescope with a circular aperture. This pattern is called Point Spread Function (psf).



The size of the image is proportional to the wavelength and inversely proportional to the diameter of telescope

The larger the telescope, the sharper the image.

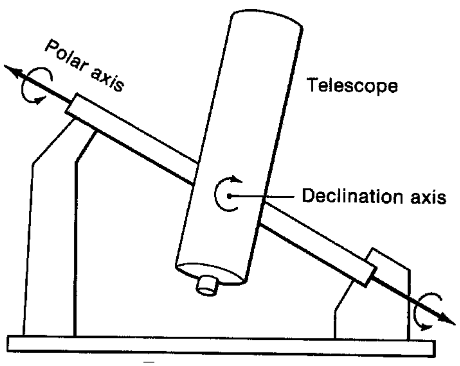


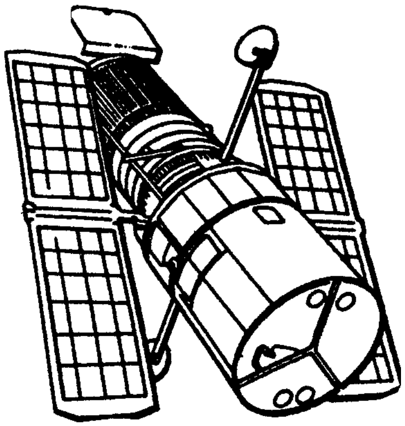
Resolution is a measure of how well one can distinguish the images of two nearby sources. Resolution is proportional to λ /D.

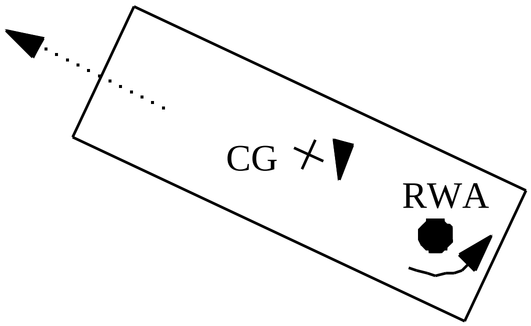
For HST: D=2.4m, λ=0.6 μ

For NGST to have the same resolution at λ=2 μ , one must have D=8m.

Pointing



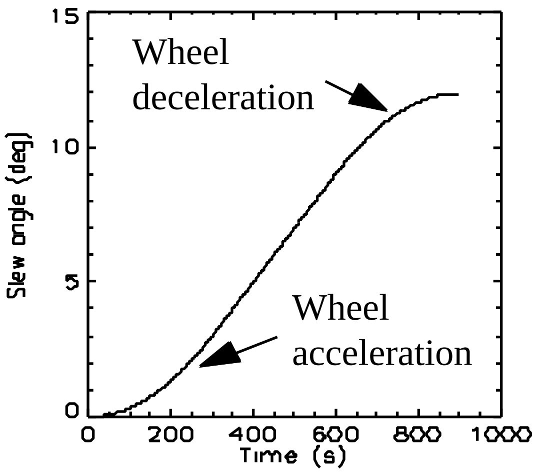




Ground telescopes are slewed by applying torques reacting against the ground

Space telescopes are slewed by momentum transfer, using:

- mass ejection (gas jets, ions),
- angular momentum amplitude change (flywheels - RWA),
- angular momentum direction change (gyroscope -- CMG)



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Sensitivity

Exposure time needed for detection or analysis of a point source in background limited mode:

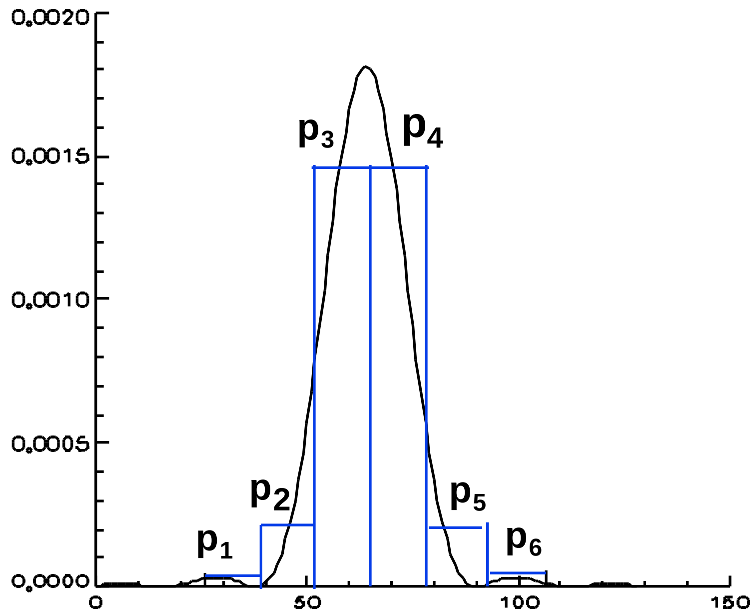
$$t = \frac{B \times SNR^2}{I^2 A \Psi}$$

where B is the background noise,
I the source signal,

A the collecting area and

Ψ the psf sharpness function (Σ psf^2)

(Burrows, 1996)



$$\Psi = p_1^2+p_2^2+p_3^2+p_4^2+p_5^2+p_6^2$$

To maximize sensitivity:

- **sharpen psf (Ψ)**
- **increase collecting area (A)**
- **minimize background (B)**

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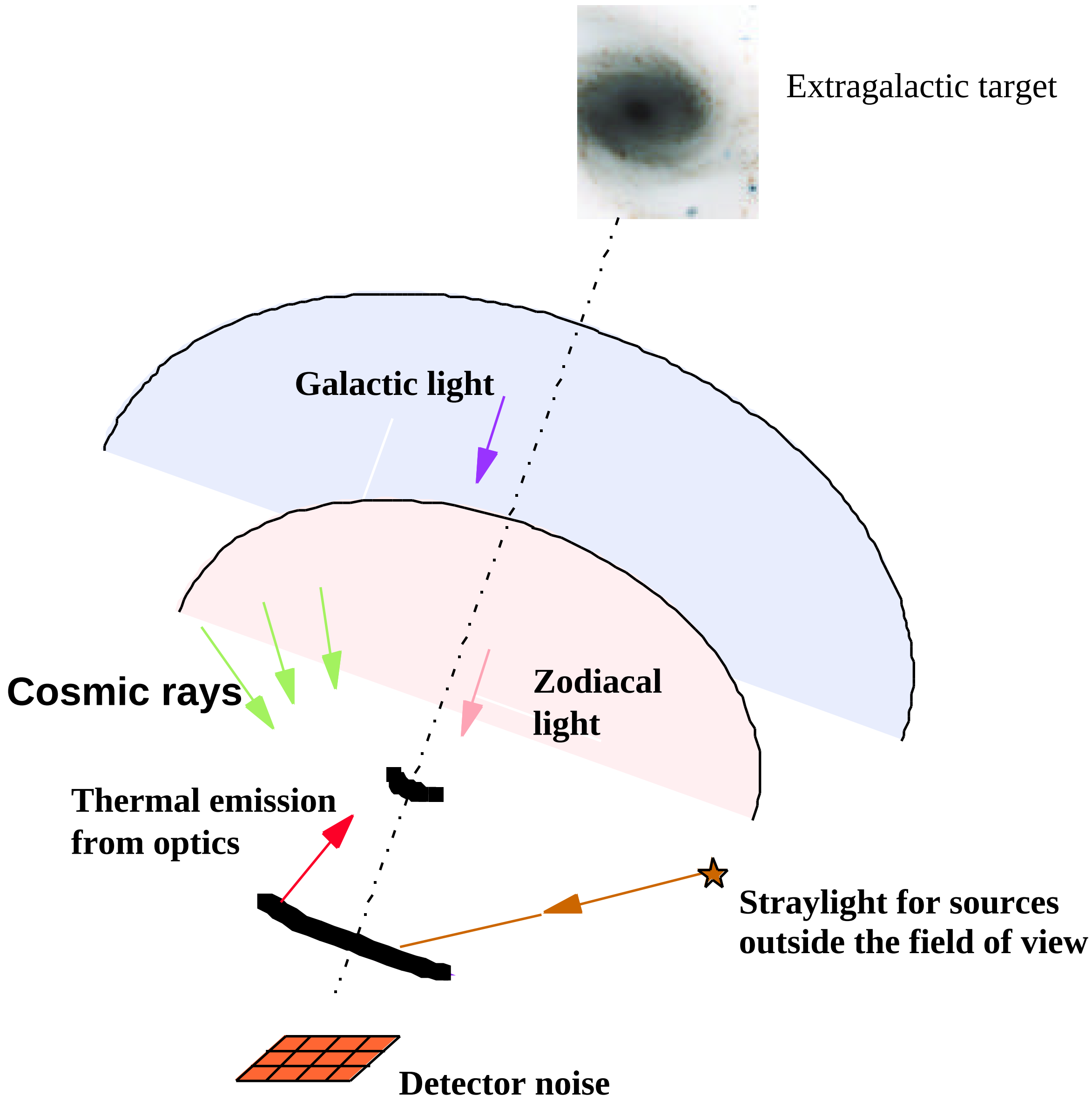
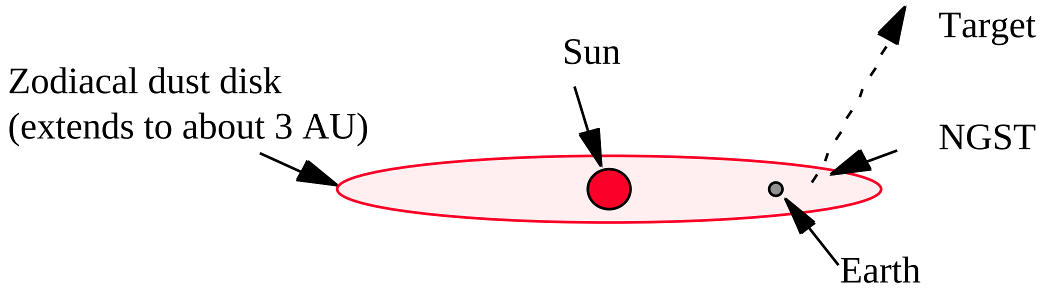
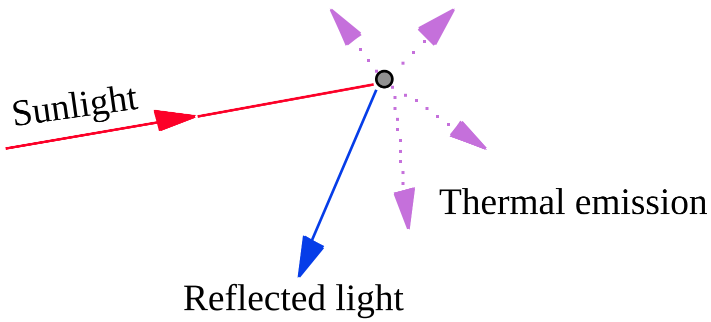
Backgrounds



Next Generation Space Telescope

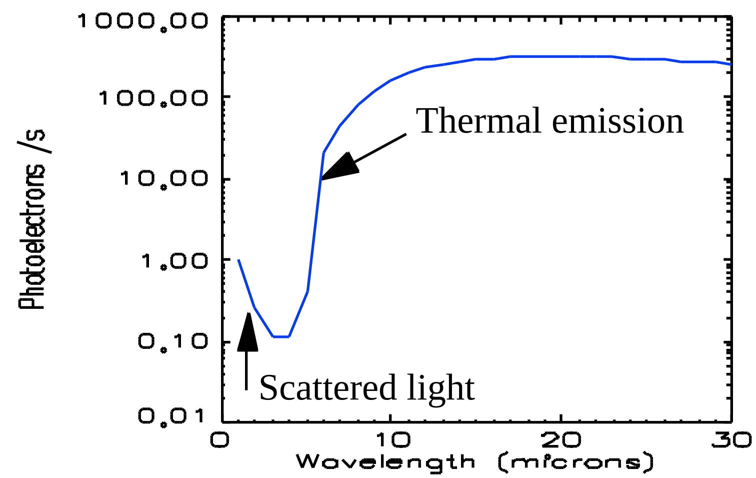
Zodiacal Background





Dust particles:

- reflect light from the sun (visible light)
- are heated by the sun (to about 265K) and re-emit in the infrared



Flux from zodiacal light in an 8m NGST with 20% bandpass

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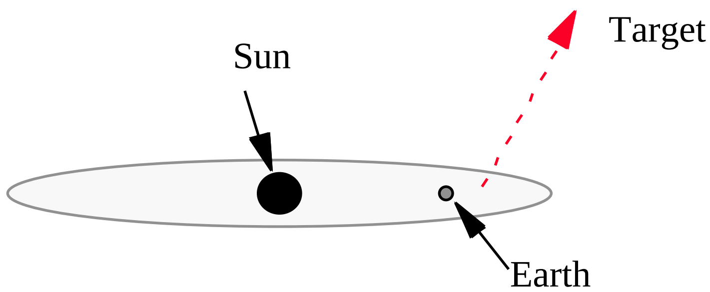
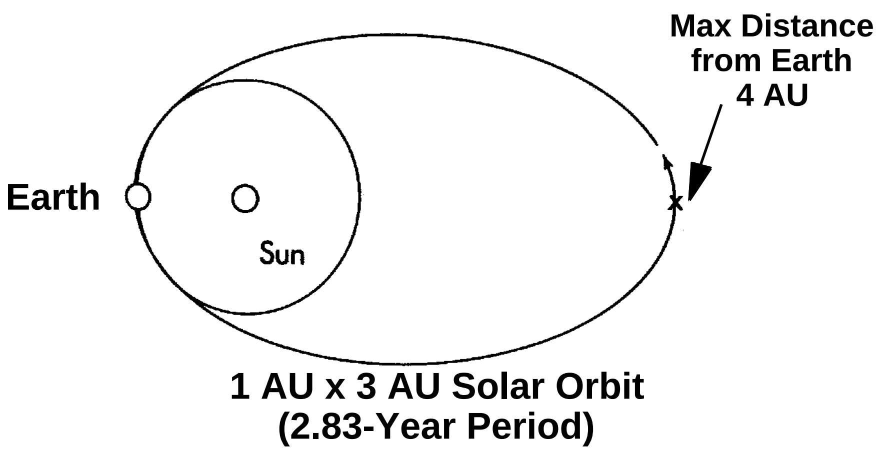
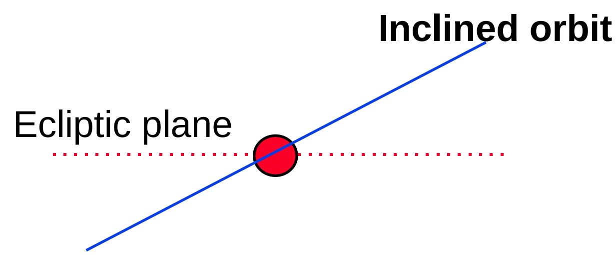
How to minimize the zodiacal background?

• **Near the earth: select targets where zodiacal light is minimal**



• **Select an orbit which takes NGST outside of the major part of the dust**



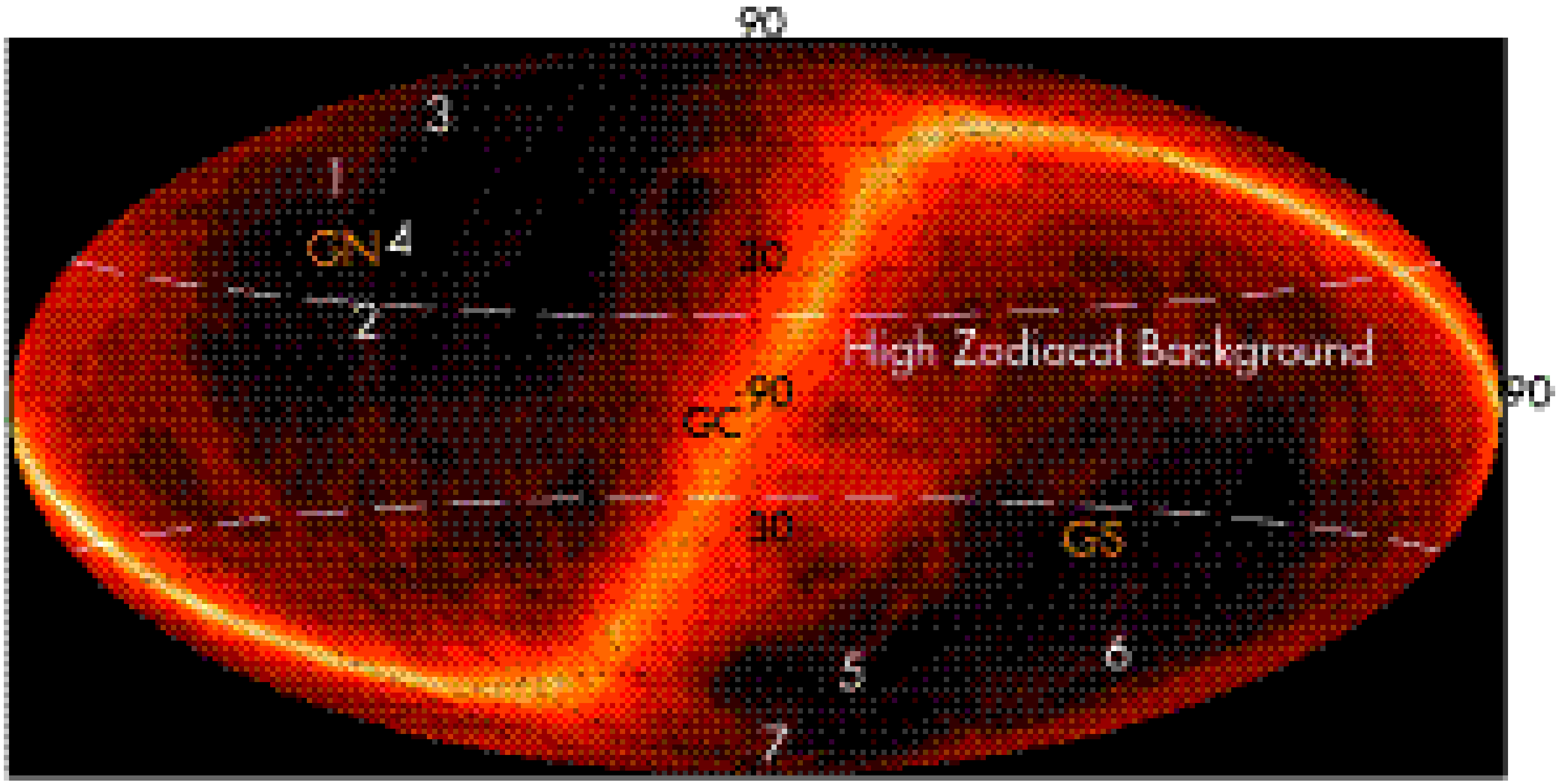


a) going further in the ecliptic plane
(at 3 AU the zodiacal light is 1/100 fainter)

b) selecting an inclined orbit
(orbit tilt must be at least 15deg)

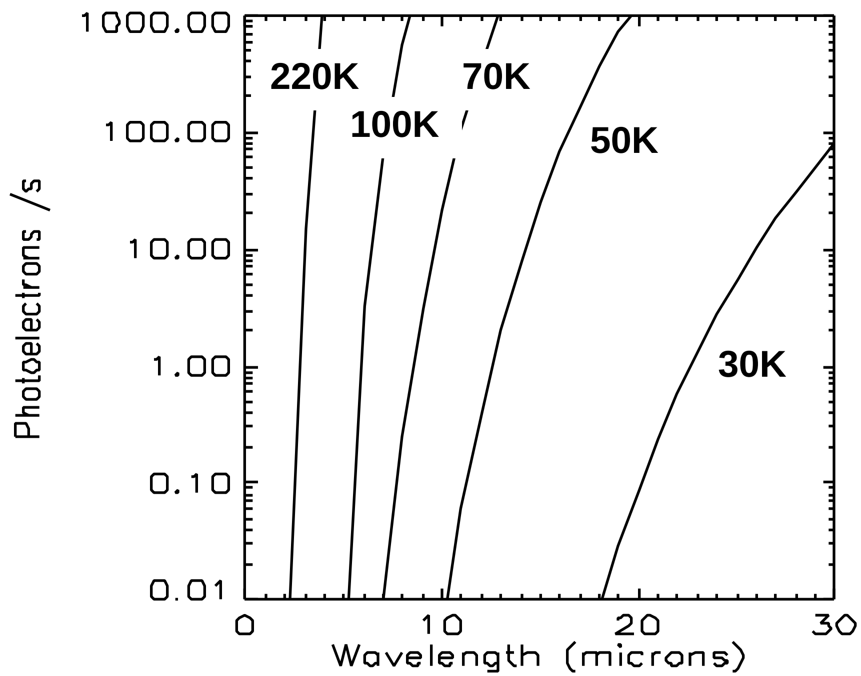
How to minimize the galactic light?

Observe near the galactic poles



How to minimize telescope self emission?

Cool the optics:



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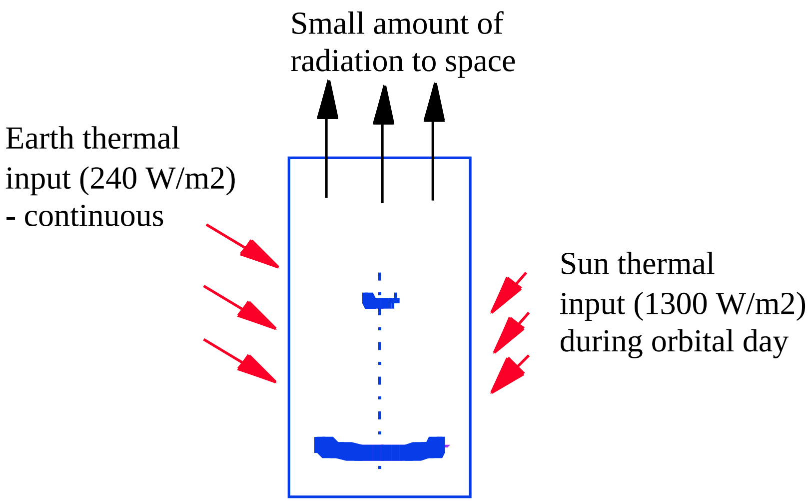
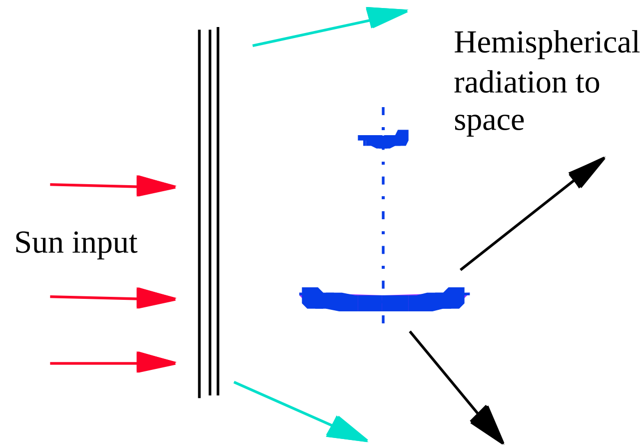
Passive Cooling

At very low temperatures, cooling by radiation is very ineffective (0.02 W/m2 for mirror at 60K with 0.03 emissivity), and requires large views of space.





In low earth orbit, long baffles are required to protect the optics against sun and earth. This makes it difficult to go below 150 K passively. Bringing the mirror and the instruments down to 60K would require > 1kW of cooling power - Problems:

- **very large solar arrays**
- **vibration**

In high orbits (HEO, L2, drift) the earth subtends a small angle and baffling can be minimal. Thanks to the large view of space, temperature down to 60K or less can be reached passively.

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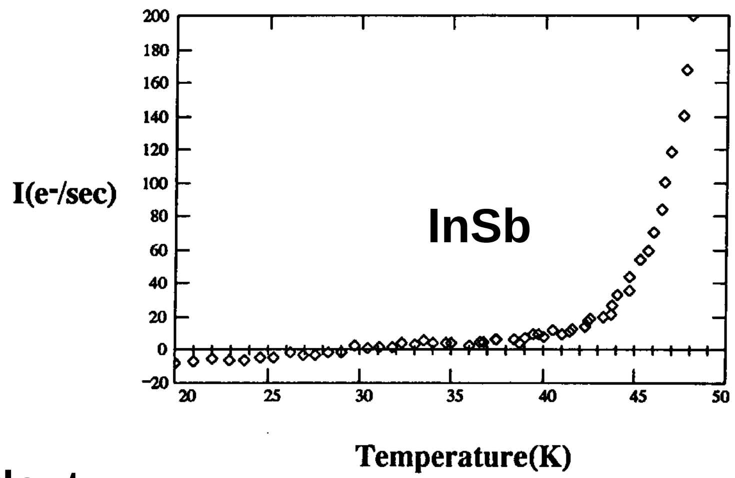
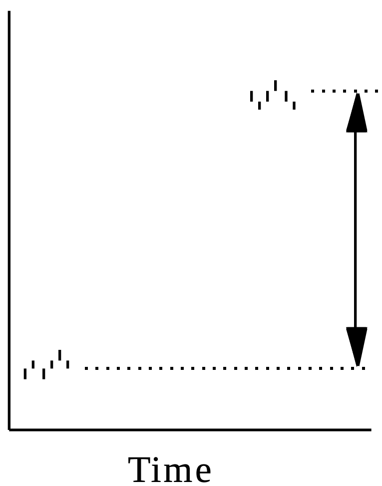
How to minimize detector noise?

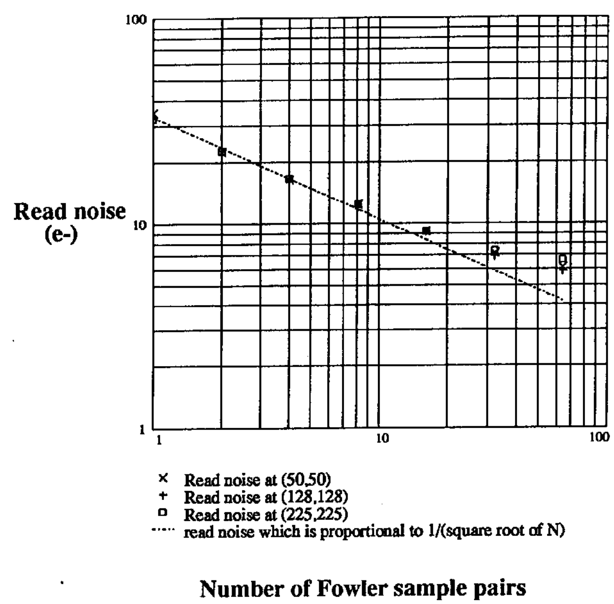
1. Cool detectors to reduce dark current



2. Multi reads to reduce readout noise



Fowler sampling



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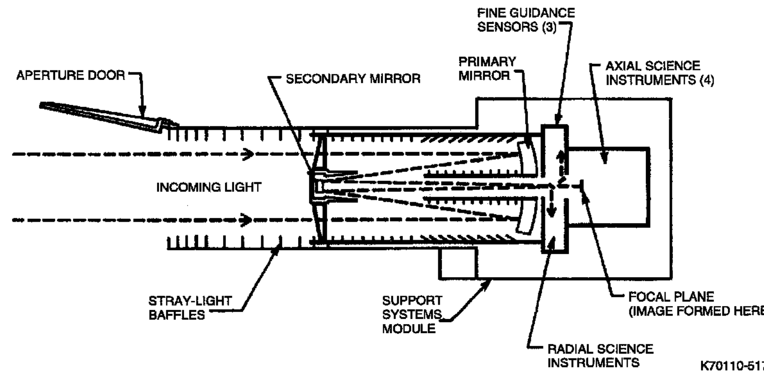
How to minimize the effect of cosmic rays?

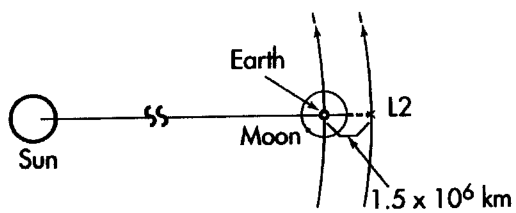
- At L2 cosmic ray rate is about 4 proton/cm^2 s
- Contrary to the photographic plate and CCD detectors, there is no penalty for making intermediate reads on an IR detector.
- Strategy is to
  - shield detectors to absorb low energy protons (<70MeV) - a few kg per detector
  - limit exposure to about 1000s (10% pixels hit) add all individual frames after "software cleaning"

How to minimize straylight?

- Extensive baffling as used on HST is inappropriate for NGST because it prevents passive cooling

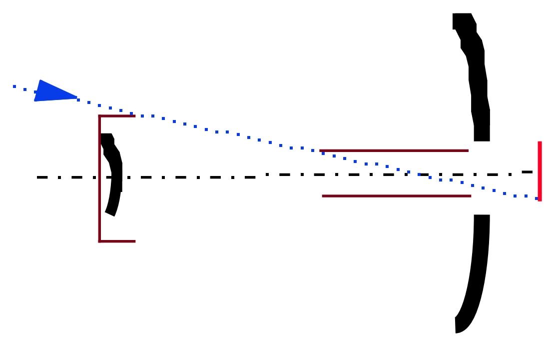


- Select an orbit where the sun, earth and moon can be easily shielded (L2 is ideal)



Sun, Earth and Moon are all on the same side of the shield

- Use baffles around secondary mirror and around return beam



No direct ray from an outside source can hit the detector

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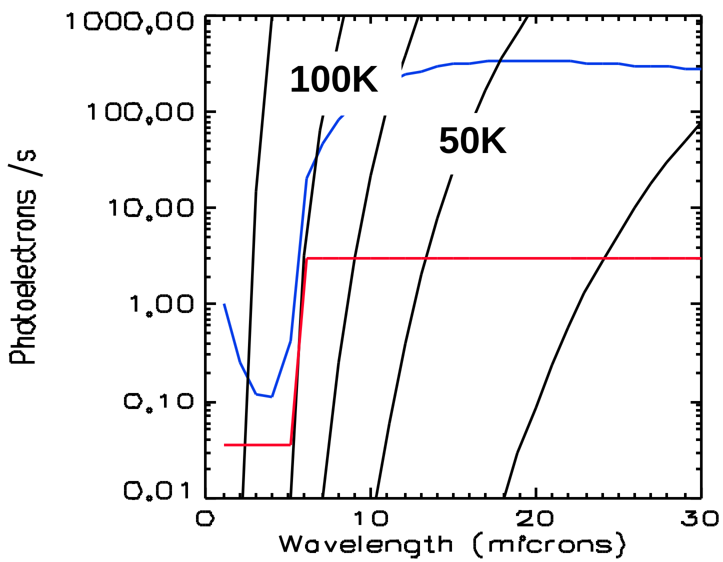
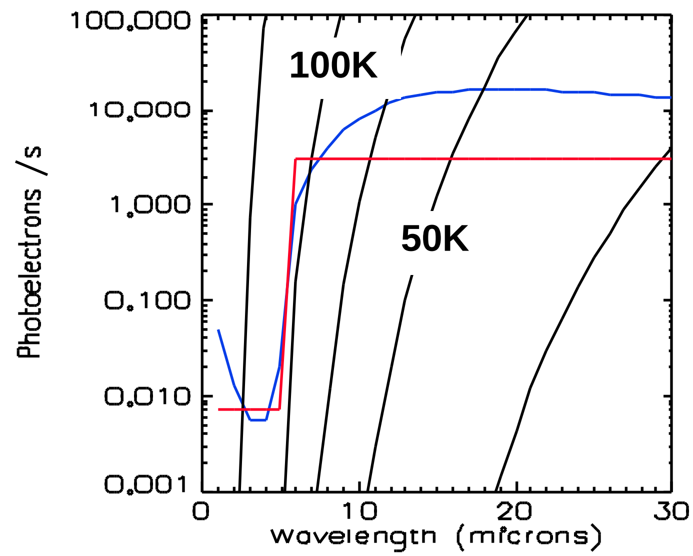
Strategy for overcoming backgrounds

Imaging -- 20% bandpass



Spectroscopy-- R=100



(note different y-scale)

Strategy:

1. **Observe where zodiacal and galactic light are minimal**
2. **Cool optics to 100K for NIR and at least 50K for MIR**
3. **Reduce detector noise to at least::**
   dark current <0.02 e-/s (NIR) 1 e-/s (MIR)
   read noise < 15 e-/read
   (and if possible 5 times better in the NIR to optimize spectroscopy)
4. **Break up exposures in 1000 s frames to minimize effect of cosmic rays**

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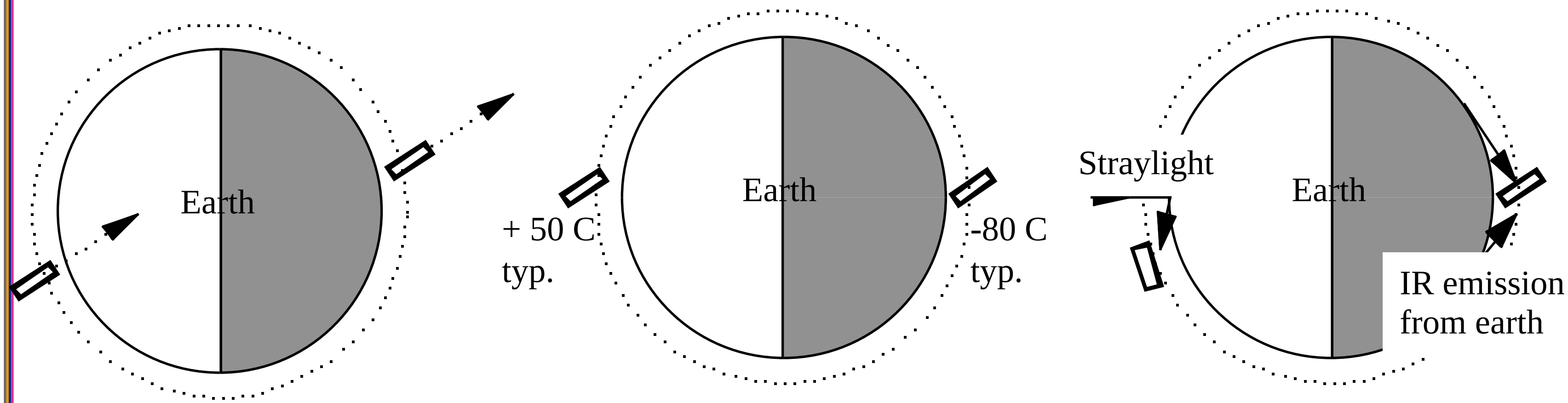
Low Earth Orbit is a poor location for a space infrared telescope



Observing efficiency is poor because of frequent eclipsing:

- roughly half of the time is lost because a target is visible only during part of the orbit (about 40 minutes per orbit)
- long exposures require that the target and guide star be reacquired.

Thermal torture

Alternating orbital days and nights induces thermal stresses which can result in optical misalignment and pointing errors.

Earth radiation

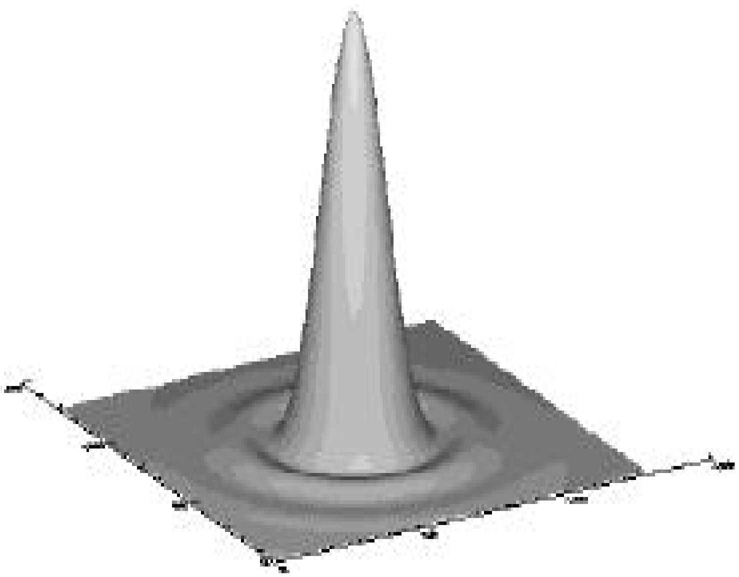
• Heat input from the earth is significant (240 W/m2) and prevents passive cooling of the optics.

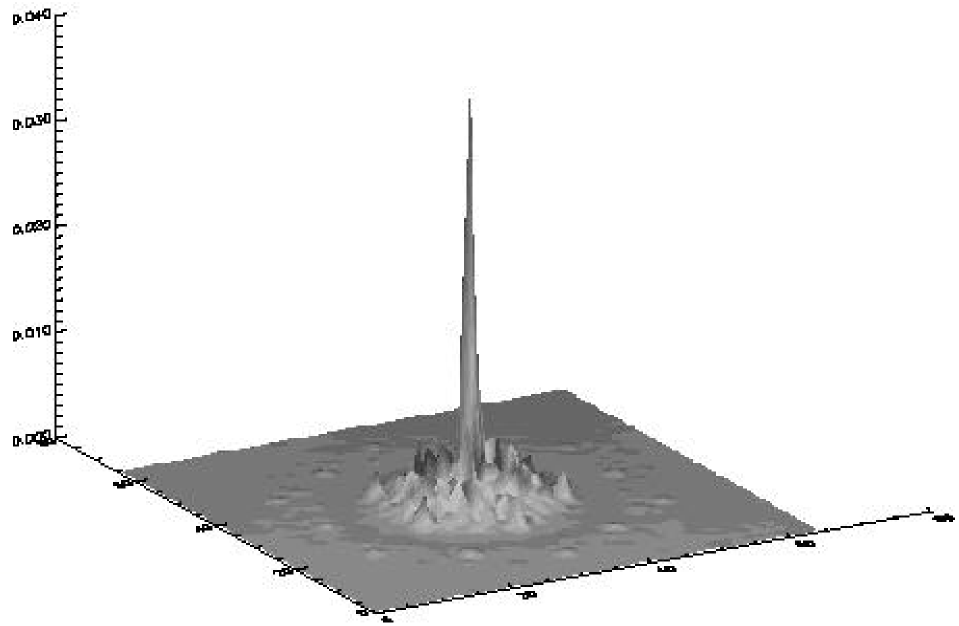
• The telescope must be well baffled to minimize straylight from both sun and the bright earth.

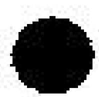
Note: the only advantage of LEO is the lower cosmic rays rate

PB:13-Jan-98

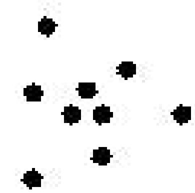
Typical Filled and Unfilled aperture PSFs







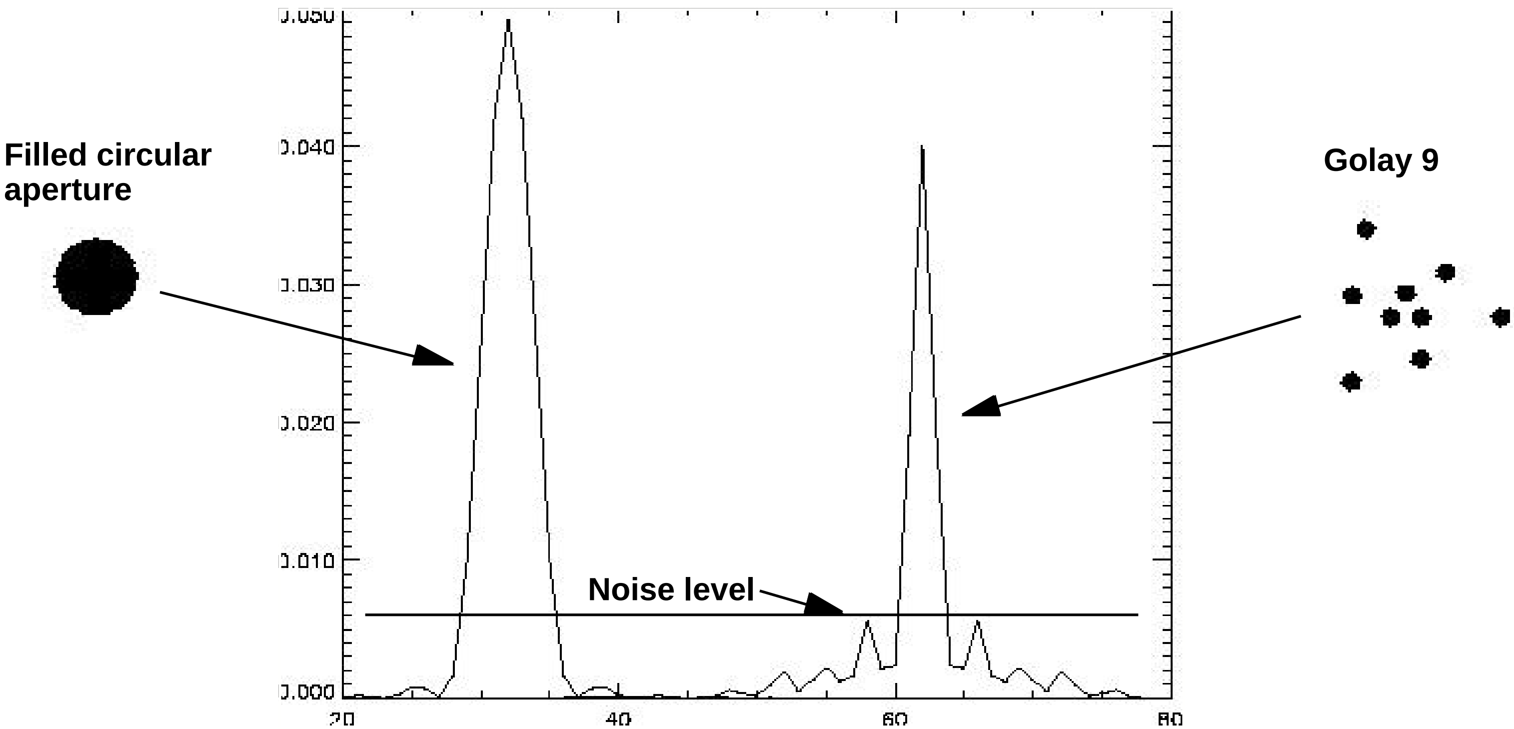
Filled circular aperture



Golay 9

Next Generation Space Telescope

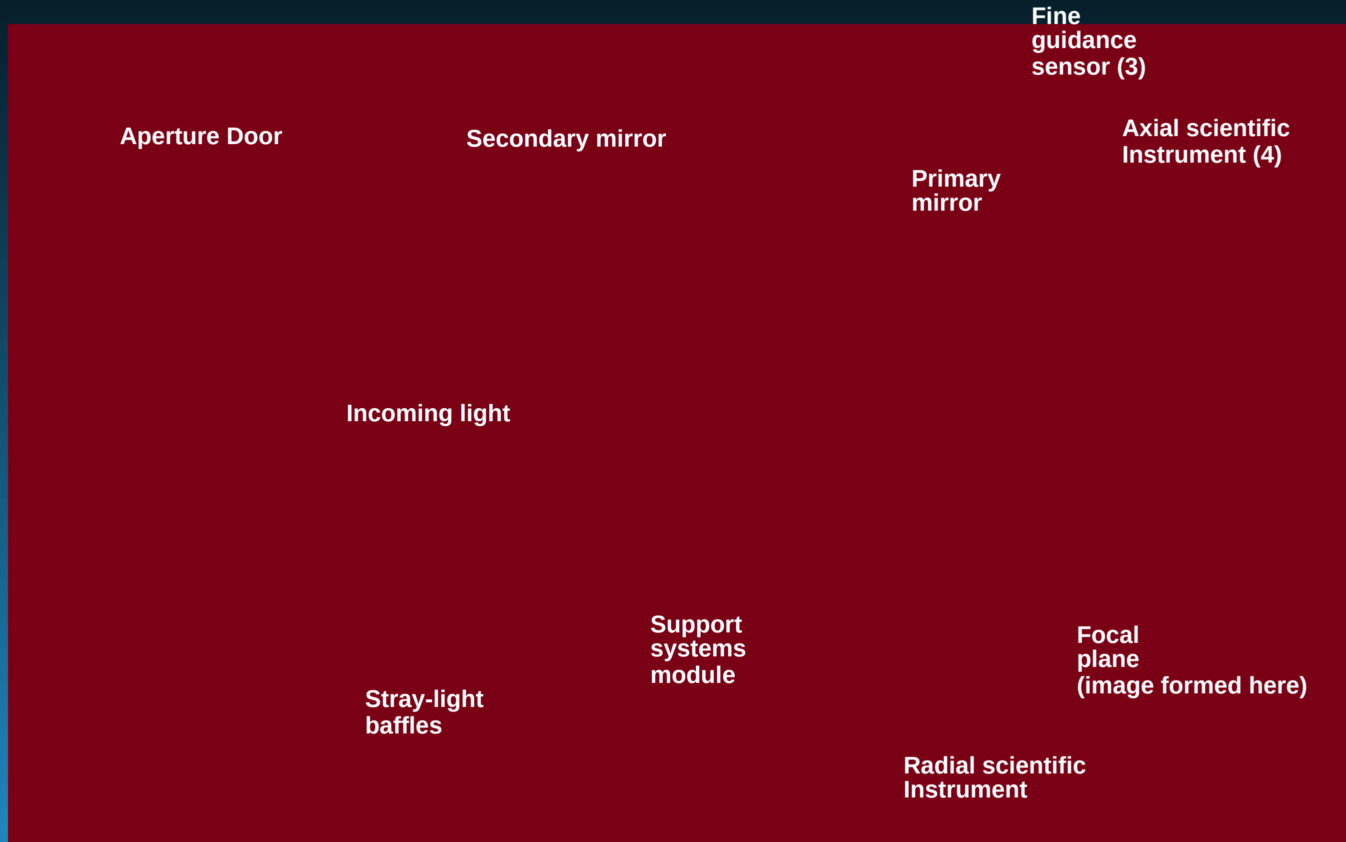
A COMPACT APERTURE IS ESSENTIAL FOR BACKGROUND LIMITED OBSERVATIONS



For the same collecting area, an unfilled aperture
- **has a higher spatial resolution (narrower core)**
- **but the peak intensity is lower and the non negligible amount of light in the wings is lost in the background noise and cannot be recovered by image processing.**

Next Generation Space Telescope

Anatomy of a Traditional Space Telescope



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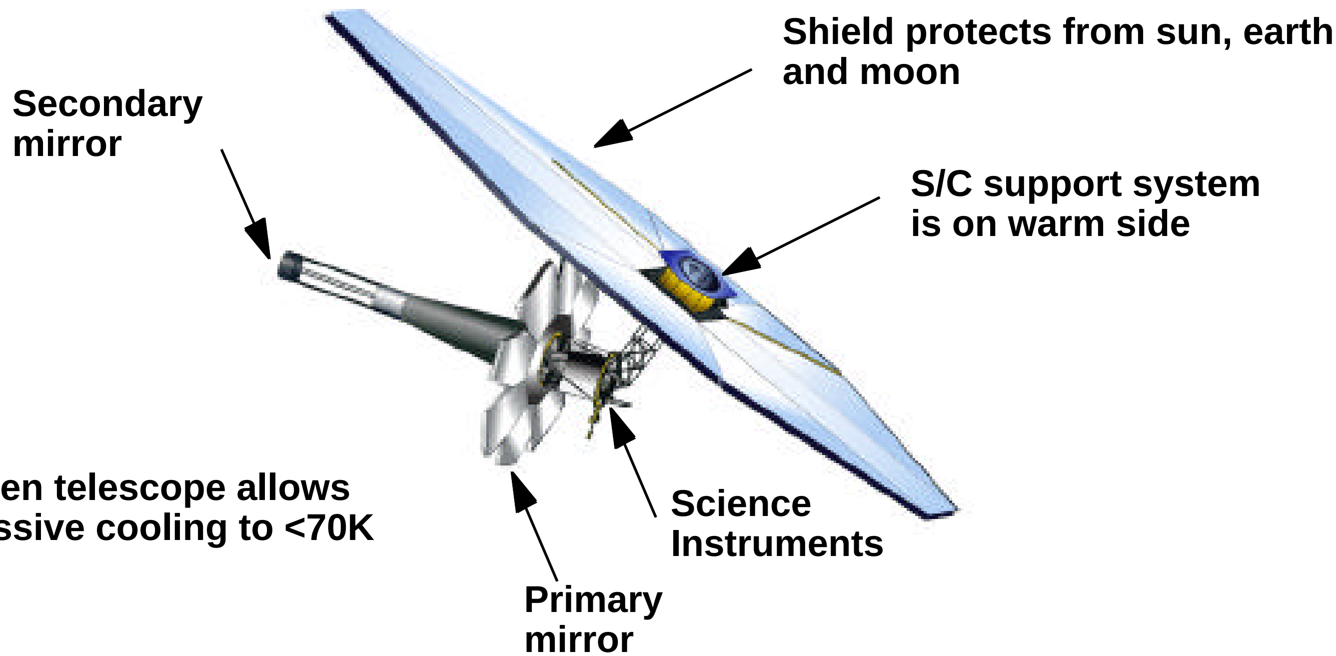
Anatomy of an Infrared Space Telescope



Terminology:
OTA= Optical Telescope Assembly
ISIM= Integrated Science Instrument Module
SSM= Space Support Module

Active Optics

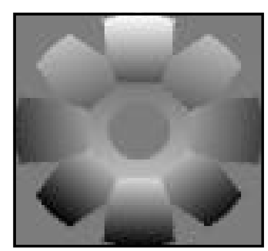
Active Optics: active control of the <u>alignment</u> and <u>figure</u> of the optical elements in the train. Typically the active control is done either slowly or intermittently.

Adaptive Optics: same but at high rate (typically milliseconds)

- **NGST does not require Adaptive optics (very slowly changing environment), but active optics is very beneficial.**
- **Advantages:**
  - **the optical elements do not need to be "perfectly made nor perfectly stable" (they can be corrected while in use)**
  - **the active control of the optics position and figure can compensate for errors due to thermal effects, line of sight jitter, structural vibration**
- **Two approaches:**

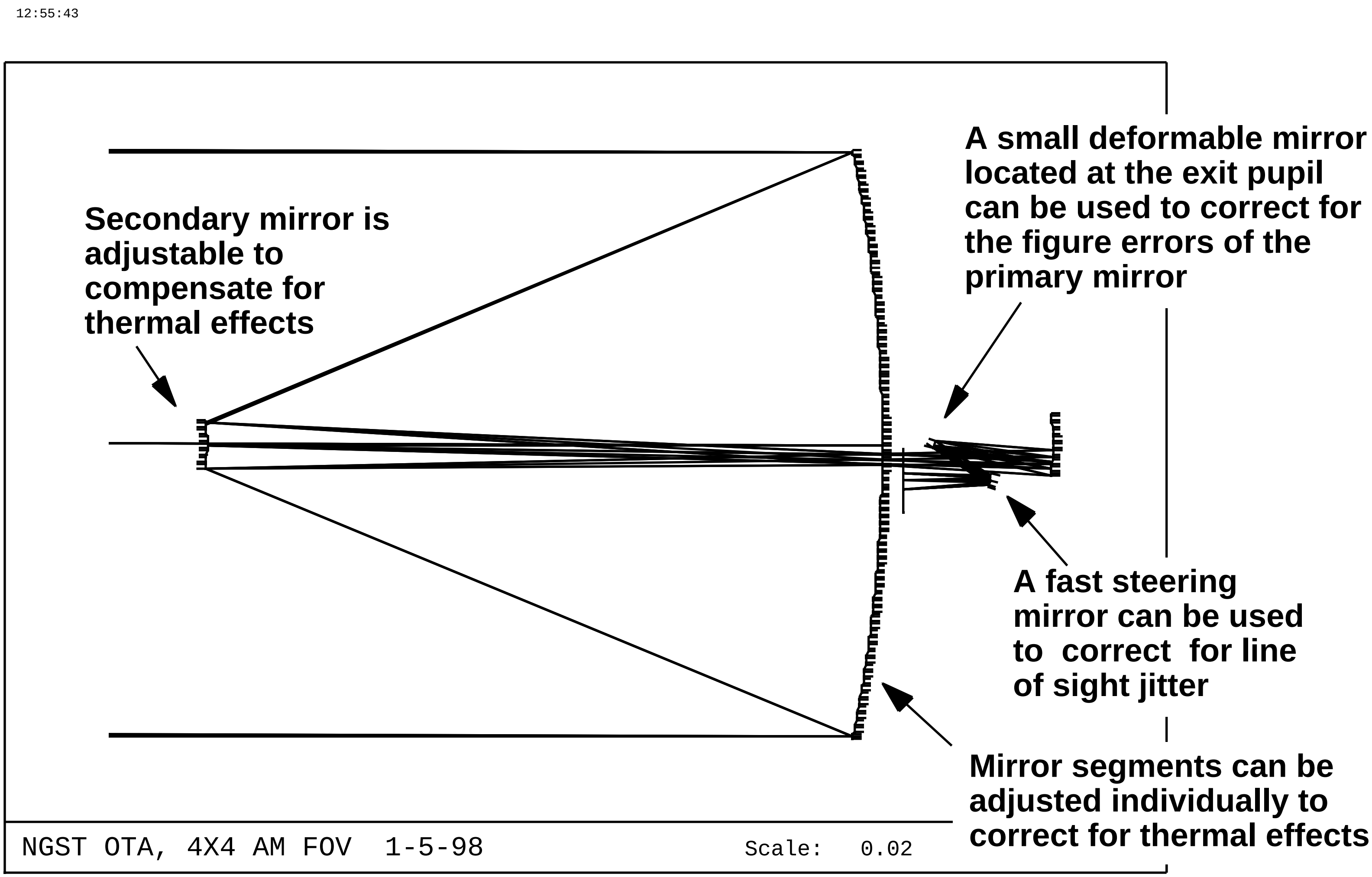
  1. metrology-based, e.g. "optical truss"

  2. image-based wavefront monitoring



Next Generation Space Telescope

Active Optics



Next Generation Space Telescope

SRB

Systems Engineering

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NGST Systems Engineer

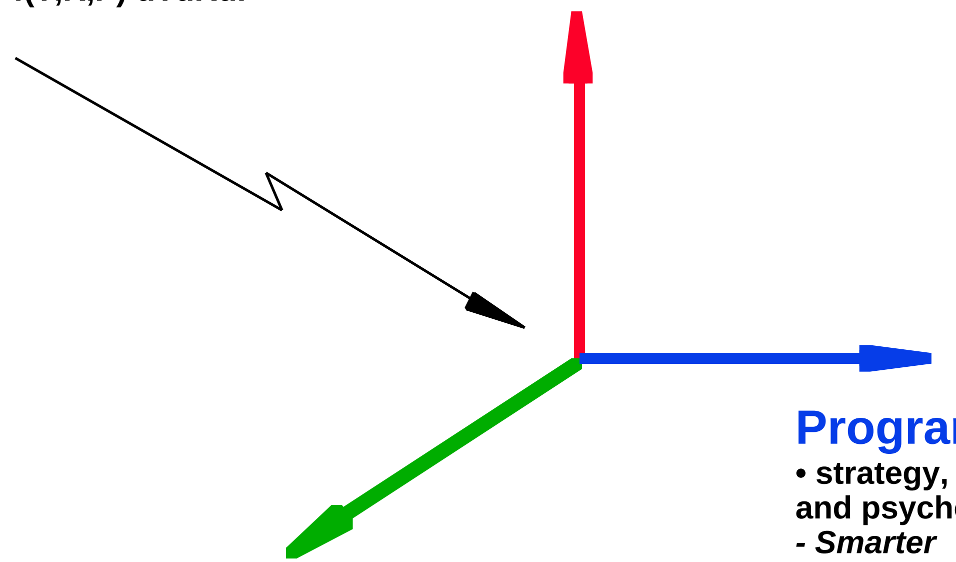
Contents

Systems Engineering Trade Space

Technical
- **scientific and technical performance**

- Better

Systems Engineering
$$= \int\int\int f(T,R,P)\, dT\, dR\, dP$$



Programmatic
- **strategy, management approaches, and psycho-social dynamics**

- Smarter

Resource
- **money & time, i.e. cost & schedule**

- Cheaper, Faster

<u>Risk</u> is uncertainty in measurable parameters within the trade space, which can be assessed and managed

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Risk

- **Risk = Uncertainty (measureable, manageable, containable)**
- **Managing Risk/Containing Uncertainty/Reducing Vulnerability/Hedging:**
  - **Technical Dimension (easiest to quantify)**
    - develop diverse portfolio of technologies
    - validate performance with hardware to retire risk early to achieve readiness
    - budget requirements thoughtfully and allocate adequate performance margins
    - implement elegant and fault-tolerant design
  - **Resource Dimension**
    - invest wisely and meaningfully early (pre dev funding > 15% of dev funding)
    - validate cost relationships to <10% with hardware demos at ≥ TRL 6
    - weigh cost heavily in technical requirements and margin allocation
    - establish stable funding profile
    - allocate and hold prudent funding and schedule reserves
  - **Programmatic Dimension (hardest to quantify)**
    - apply validated management practices (proven old ones, tested new ones)
    - recruit and retain good people
    - seek and apply institutional expertise and excellence
    - establish partnering and buy-in
    - reach out to public and scientific community
    - advance technological SoA and maintain scientific significance and relevance
    - negotiate “win-win” and use “results-oriented” contracts

Metrics

- Unambiguously define targets (so you know where you're going), measure progress (so you know where you are), and determine compliance (so you know if you've made it)
- Enable rational measurement and assessment; move away from idealogy and handwaving and toward the scientific method, logic, and objectivity
- Enable effective contracts and clean agreements
- Allows for quantified, effective cost/benefit analysis

Progress Metrics

Technical

– **Time to complete DRM** where exposure time = B x SNR^2 / I^2 x A x Ψ
  where B is background noise, I is source signal, A is collecting area, and Ψ is PSF sharpness
  – besides as a measure of compliance with mission requirement, used to assess need for technological development as well
– **Scientific Relevancy,** based on ranking by NASA's science advisory committee
  – serves as a check on the DRM's vitality
– **Technology Readiness Level (TRL),** where TRLs are NASA definition
  – measures technological readiness
– **System Performance Effectiveness,** where performance = speed x FOV / cost
  – basis for comparison to other observatories

Resource

– **Schedule Milestones** (tech readiness date, launch date, DRM complete date)
– **Schedule and Cost Variance** (from GAAP, in dollars, <10%)
  – compliance with mission requirements/constraints

Programmatic

– **Compliance with Origins theme and strategic plan (ASO)**
– **Compliance with NASA Procedures and Guidelines (NPG 7120)**

Project Objective and Requirements

- **Project Objective: Develop and Operate NGST to Accomplish the DRM in less than half the minimum mission lifetime within established resource constraints by executing a deliberate program plan**
- **Project Requirements**
  - **independent of trades**
  - **forms basis of trades and design**

ITEM	REQUIREMENT	GOAL
Scientific Throughput	complete core DRM in 1/2 ops lifetime	complete entire DRM in <1/2 ops lifetime
Total Lifetime	5 years	>10 years
Spectral Coverage	NIR (1-5μm)	Visible-MIR (0.5-30μm)
Field of View	wide-field	wide field
Spatial Resolution	diffraction limited at 2μm (0.050”)	diffraction limited at 2μm (0.050”)
Spectral Resolution	$\Delta\lambda/\lambda$ up to 1000	$\Delta\lambda/\lambda$ up to 1000
Limiting Sensitivity	zodiacal light background	cosmic background limited
Aperture	>4m diam. nearly filled aperture	>8m diam. nearly filled aperture
Instrument Capabilities	wide-field imaging, multi-object spectroscopy	wide-field imaging, multi-object spectroscopy, coronagraphy
Cost Cap	develop and validate enabling technologies at TRL=6 for < \$230M $_{96}$ develop system for <\$500M $_{96}$ launch and operate (based on 10 year total lifetime) for <\$400M $_{96}$	develop and validate enhancing and enabling technologies at TRL=6 for < \$230M $_{96}$ develop system <\$500M $_{96}$ launch and operate (based on 10 year total lifetime) for <\$400M $_{96}$
Resource Variance	<10%	0%
Program Conduct	NPG 7120 compliant, ASO strategy compliant	NPG 7120 compliant, ASO strategy compliant

Requirements Flow

- Requirements flow out <u>and</u> back in iterative, convergent fashion
- Systems Engineer is steward of the systems engineering process; Mission Architect is executor of process
- Systems Engineer documents requirements and manages their flow; Mission Architect designs system architecture

Project Rqmts	Architecture Rqmts	Segment Rqmts	Element Rqmts	Subsystem Rqmts	Component Requirements	Parts Rqmts
mission	system	space ground launcher	SI module OTA Ops Physical Plant Ground Term Control Center Mission Planning	Cameras Spectrometers Coolers PM SM Tower Backing Structure C&DH Comm Thermal Control	mirror assys FPAs Actuators edge sensors fringe sensor sunshade boom radiator FSM DM SI computer S/C computer antennas harnesses terminals	fasteners op amps machined parts capacitors resistors connectors . . . . . .

Systems Engineering Process

SRBfig 131

Design Reference Mission (DRM)

- **The DRM is a quantified observational/operational manifestation of the scientific objectives as described in the HST & Beyond report**
- **Different system architectures are compared by simulating their execution of the DRM and measuring the time required and assessing their robustness**

Programs	Modes	Flux Level (nJy)	No. of Obs	Total Time (days)
Early Formation of stars and galaxies	NIR NIRS	0.4-270	393	204
Structure and dynamics of galaxies at z>2	NIR NIRS MIR MIRS	0.4-4 4-280 80-350 1000	3347	554
Distant supernovae	NIR NIRS	1.4 2.8	817	485
Nature's telescope	NIR	70	179	20
Stellar populations in nearby universe	NIR MIR	0.6-2.3 600-5000	517	355
Solar System	NIR MIR	3-1000 140-1000	1648	99
Protostellar systems and studies of the IMF in star forming regions	NIR NIRS MIR MIRS	2-10000 70-10000 100-1000 >1000	2400	20
Individual object classes	NIRS MIR	70-1000 66-16000	668	222

Trade Space

SRBfig 129

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Integrated High Level Trades

- **NGST is a multi-purpose observatory system. Some proposed observations have conflicting requirements**
  - **surveys need wide field-of-view, but pointed observations do not**
  - **sensitivity is more important for spectroscopy than imaging**
  - **MIR observations much more affected than NIR by "warm" optics**
  - **some targets are extended sources with complex morphologies which need higher spatial resolution than point sources**
  - **some observational sequences are operationally more difficult than or exclusive of others**
- **NGST cannot be ideal for all observations, so intra- and inter-dimensional trades are performed to reach compromise that satisfies Project Requirements (technical, resource, and programmatic)**
  - **more than one *possible* solution**
  - **determination of *optimal* solution difficult because of subjectivity and non-linear nature of trade space**
  - ***optimal* solution a function of taste, culture, various programmatics**
- **DRM used as a standard study case to flush-out mission drivers, enable productive high-level trades, and establish *Architecture Requirements***

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Integrated Trade Methodology

- Examine limiting sensitivity as prime figure of merit
  - exposure time = B x SNR^2 / I^2 x A x Ψ where B is background noise, I is source signal, A is collecting area, and Ψ is PSF sharpness
- Understand fundamental cost relationships
  - OTA cost goes roughly mass, or $D^{2.7}$
  - Instrument cost grows with physical size of Field of View, proportional to angle * D^2
  - Improved Detector Noise exponential
  - Spacecraft segment costs go as $a + b*D^3 + c*D^2$ where b represents items whose costs scale with mass (e.g., ACS) and c represents items whose costs scale with size (e.g., sunshade)
  - incremental costs
    - active cooling (for Si:As detectors if desired)
    - cost of larger, unavailable shroud
- Trade based on combination of limiting sensitivity and cost (traceable to project requirements)

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Integrated High Level Studies and Trades

- System-level/inter-element
  - orbit vs launcher/orbital insertion capability
  - ground vs on-orbit checkout/assy (robotic servicing, EVA)
  - sky coverage
  - launch vehicle/shroud configurations
  - lifetime and reliability
  - ops strategy and tactics
  - data processing distribution (on-board vs ground)
  - operational on-board autonomy
- Observatory element
  - telescope diameter
  - aperture configuration
  - allowable detector noise
  - mirror temperature
  - allowable line-of-sight jitter

Integrated High Level Trades

- **Segment Trades**
  - **mirror segmentation and deployment scheme**
  - **mirror material and technology**
  - **wavefront control**
  - **custom vs commercial spacecraft support module (SSM)**
  - **passive and active vibration control**
  - **focal plane geometry and shared functionality (guiding, wavefront control, observing)**
  - **PSF vs mirror gaps/geometry**
- **Subsystem Trades**
  - **wavefront sensing**
  - **spectrograph configuration**
  - **comm technology**
  - **sunshade inflation vs erection**
  - **cryocoolers**

Notional Architecture Requirements

- System characteristics
  - launcher: Atlas IIAS (lift/shroud/cost equivalent)
  - telescope orbit: L2
  - sky coverage: full over one year
  - flight segment mass: 2800kg
  - flight segment power: 800W
  - ground station: 11m dedicated
  - telescope diameter ≥ 7m
  - aperture configuration < 5% gaps & notches (deviation from filled aperture of same optical configuration)
  - allowable detector noise and dark current < 0.02 e^-/s
  - sensitivity: 4nJy (for 10000s integration at 2µm, 20%BP to achieve SNR = 10)
  - mirror temperature < 70K
  - pointing accuracy: 2”
  - allowable line-of-sight jitter: 0.010”

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Architectures

- Architecture = The mission system construct, as manifested in hardware, software, and operational schemes, existing in place on the ground and in space
- Reason for Multiple Architectures:
  - Although Project Requirements are unique, solutions to them are not
  - Added thinking breeds more and better ideas
  - Multiple viable approaches reduces risk
  - Competition is fostered, yielding better results
- Role of Reference Architecture:
  - Educates the customer via the case study method about the key issues and challenges of NGST
    (I hear, I forget; I see, I remember; <u>I do, I understand</u>)
  - Defines a benchmark for competition to meet or exceed
  - Serves as a standard for comparison with alternative architectures
  - Serves as a vehicle for identifying enabling technologies and defining technology development guidelines and specifications
  - Serves as a subject for integrated end-to-end modeling

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Incremental Cost/Benefit of Technology Development

- Cost containment through judicious technological investments
  Question: how much to invest?
- Trades fall into two categories:
  - direct savings/enabling technology (needed to simply meet project requirements)
  - offset savings (cost of implementation traded against another parameter, typically collecting area)
    - limiting sensitivity to detect a point source as the technical objective metric (F_{lim} ~ snr (B/*AT)1/2). The cost of building the OTA is used as the cost metric and is taken to be C~K A2.7/2, where K is taken to be as $100m (the nominal allocated cost of the OTA). Assuming once a mirror technology is chosen the traditional scaling law holds.

Technology Investment Cost/Benefit Direct Savings (page 1 of 2)

- **Large Lightweight Optics**
  - **Current SoA (30 kg/m2) would add 600 kg to present design plus additional mass to OTA structure. Cost proportional to weight and EELV heavy launcher would likely be necessary. Cost would be ~$100m above baseline**
  - **New lightweight technology needs ~$20m for development. *Cost savings of $80m***
- **Development of Deployable Primary Mirror Technology**
  - **Current technology (monolith) needs a new rocket shroud to enable 6m diameter primary mirror at a cost of at least $170m ($75m for shroud development + $75m for EELV heavy to reach 3AU + $20m to improve detector dark current and read noise to utilize low background 3AU orbit)**
  - **New technology of deployable primary will enable an 8m primary with an investment of ~$20m. *Cost savings of $150m***

Technology Investment Cost/Benefit Direct Savings (page 2 of 2)

- **Integrated Modeling**
  - **Current techniques do not lend themselves to optimization**
  - **Assume reduce costs through optimization by at least 10 percent (savings of $50m) at a cost of about $5m which corresponds to a five person team working for five years.** ***cost savings of $50m***
- **Cryo-actuators are a Go/No Go technology**
- **Inflatable Sunshield**
  - ***under review***
- **Autonomous operations**
- **Reducing the complexity of the operations could net 100 FTE per year manpower reduction over minimum 5 year operations.**
  cost savings: $20m

Technology Investment Cost/Benefit Offset Savings (page 1 of 2)

- Assume that if the new technology cannot be developed the primary mirror area would be increased to achieve the desired performance. Simplistically illustrates how the technology development allows required performance for minimum primary mirror area. These trades are a key component of the cost containment strategy (an additional charge for a larger rocket should be included in the estimate)
- Large format visible/NIR detectors to increase FOV
  - For surveys, Efficiency proportional to AΩT. Doubling FOV(Ω) is equivalent to doubling A(rea). $20m investment to produce low noise 2kX2k modules. C(ost) ~ $100m*A $^{2.7/2}$ (for OTA with a constant mirror technology) = $255m for a *cost savings of ~$235m*.
- Low noise visible/NIR detectors
  - F_{lim} ~ snr (B/*AT)1/2 . For a background limited observation decreasing the background by a factor of four is equivalent to increasing the area of the primary mirror by a factor of four. Since C~$100m A $^{2.7/2}$ which translates to a cost saving of over $500m.

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Technology Investment Cost/Benefit Offset Savings (page 1 of 2)

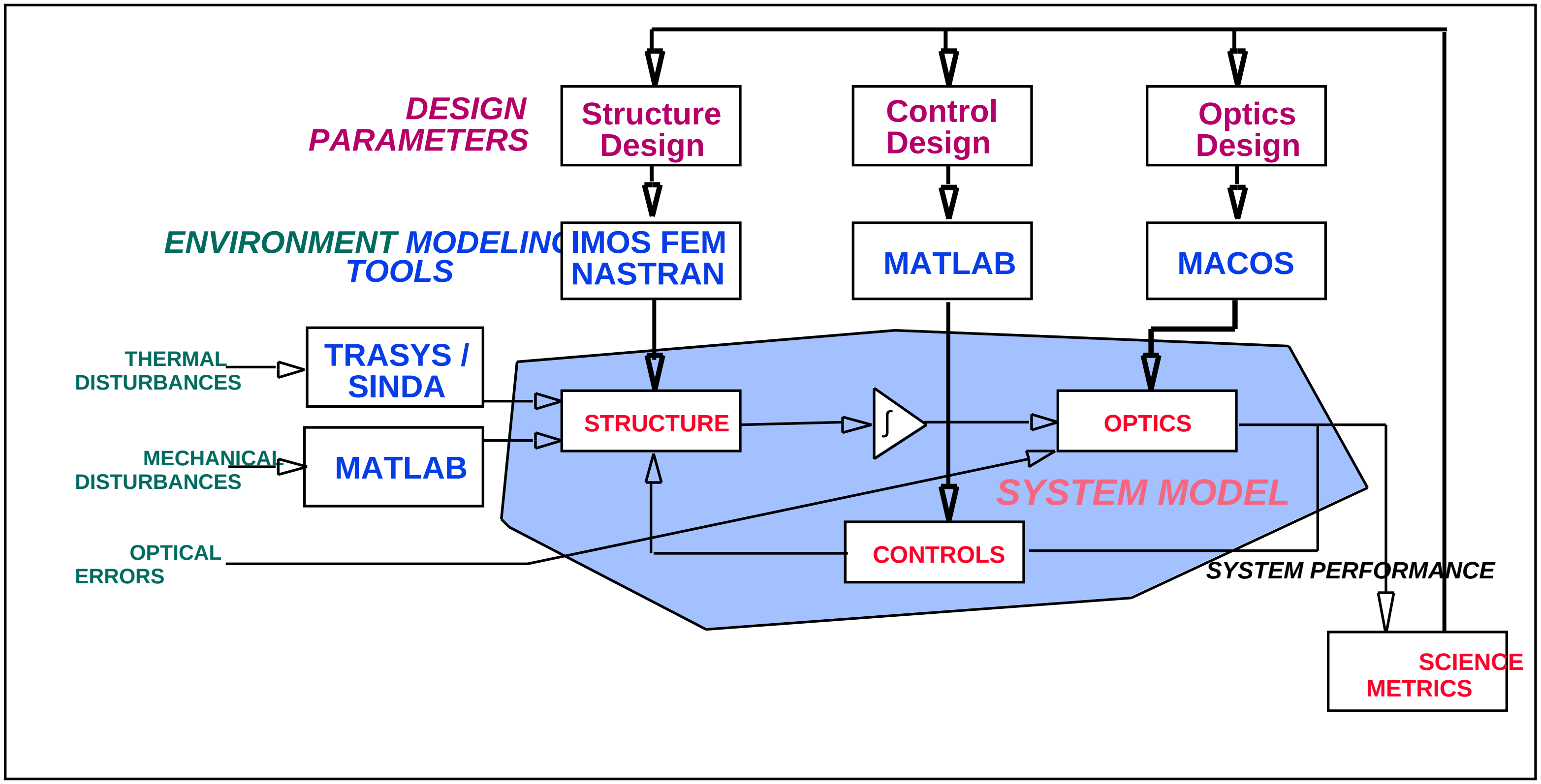
- Vibration isolation and low noise RWA
  - Standard off the shelf RWA would effectively double the sharpness parameter (Ψ) in the limiting flux calculation. An investment of ~$10m will yield a *cost savings of $250m*.
- Cryo-cooler
  - With cryo-cooler the use of Si:As IBC detector is enabled and 1e/s dark current is achievable. This compares with the 100 e/s dark current for HgCdTe detectors at LN2 temperatures. For wavelengths where the telescope background does not dominate cost savings of two orders of magnitude are achievable.

Technology Needs

- **Architecture creation simultaneously considers and identifies critical technologies and their developmental performance requirements, cost and schedule drivers, and nature of management challenges**

TECHNOLOGY NEED	PRIORITY
Optical Telescope Assembly	
· Ultra-lightweight cryogenic mirrors	1
· Cryogenic actuators	1
· Cryogenic deformable mirror	1
· Deployable structures	2
· Wavefront sensing & optical control	2
Science Instrumentation	
· Low noise, large format near IR & thermal IR detectors	1
· Vibrationless cryo-coolers	2
· Digital micro-mirror array	3
Physical Plant	
· Inflatable or deployable sunshade	1
· Vibration isolation	1
· Low temperature materials property characterization	2
· Advanced startracker	3
Operations	
· Flight software development methodology	1
· Autonomous scheduling and execution	1
· User interaction tools	2
· Autonomous fault management	3
· Control executive	3
· Data compression	3
Systems	
· Integrated modeling tools	1

Integrated Modeling in the Systems Engineering Process



- Integrated modeling is used to explore high-level design trades, validate design concepts, help guide the technology development activities, and predict performance of detailed designs.
- We are trying to design an optimized system, not a collection of optimal subsystems. The integrated performance models quantify thermal, structural, control, optics, detector and system issues in terms of science impact. The trades and optimization processes could be extended to include cost as a metric, given appropriate models.
- A tightly integrated set of software tools provides multiple analytic functions:
  - *Time-domain simulation, frequency-domain analysis, statistical analysis, optimization*
  - *Software testbed for attitude control and optical control/alignment algorithms*
- Models and tools will be validated via testbeds, experiments, and work on other projects.

Validation

- To meet requirements or achieve goals, new performance capabilities, cost/schedule relationships, and management paradigms must be developed and validated
- Modeling verifies that requirements are not wrong. Testing confirms if they are correct
- Testing verifies technical performance, defines TRLs, and establishes cost relationships. Provides technology existence proof and populates build-to-cost and schedule database
- Performance and cost models are validated and refined by correlating model predictions and test results. Updated models are used to reexamine trades that refine architecture design and generate refined design and technology development requirements

System Validation

- **Nexus Pathfinder Flight is special as *the* system-level technical, resource, and programmatic validation mechanism**
  - **Limited utility as a technology validator, but given the intrinsic value of building a flight system, it will likely flush-out and validate systems integration issues and technologies. Validity dependent on basic architectural kinship to NGST**
  - **Important resource validation, where degree of validity and fidelity is function of scaling law credibility and technical similarity**
  - **Programmatic relevance and degree of validity is a function flight build teaming and process similarity between Nexus and NGST**

Schedule

1. Project Phases
A. Mission Analysis & Design (pre-A, A, B) 1 Jan 96 thru 31 Mar 03
B. System Development (C/D) 1 Apr 03 thru 31 Dec 06
C. Launch Processing 1 Jan 07 thru 30 Apr 07
D. Deployment & Commissioning 1 May 07 thru 31 Jul 07
E. Science Ops 1 Aug 07 thru 31 Jul 17

2. Major Project Reviews
A. PMC 27 Feb 99
B. PNAR 1 Jul 00
C. NAR/PDR 1 Aug 02
D. CDR 1 Oct 03
E. TRR 1 Jan 06
F. PSR 15 Dec 06
G. LRR 15 Apr 07
H. SORR 15 Jul 07

3. Major Project Milestones
A. Begin Project 1 Jan 96
B. ISIS Pathfinder Launch 1 Jul 00
C. Single Prime Selection 1 Oct 00
D. Nexus Pathfinder Launch 1 Jul 03
E. Technology Readiness/Approval 1 Sep 03
F. System Construction & Testing Complete 31 Dec 06
G. Launch 1 May 07
H. Normal Ops Commissioning 1 Aug 07
I. DRM complete 31 Jan 10
J. Minimum Lifetime Achieved 31 Jul 12
K. Goal Lifetime Achieved 31 Jul 17

Summary

- Project Objective and Requirements are concise and clear
  - Tendency is to over-specify, which leads to over-constrained engineering
  - Only project level requirements are unique and independent of trades and design
  - Finer-level requirements are the product of trades and a reflection of design. Solutions sets are non-unique
- Systems Engineering trade space is more than technical
  - Cost, schedule, and programmatics have requirements too and are concurrent considerations
- Systems Engineering Process is inclusive, recursive, non-linear
  - DRM forms starting point for the process
  - Design and technology development requirements are not one-way. They are refined and validated through the interaction of modeling and testing